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ROYAL AIRCRAFT ESTABLISHMENT

FARNBOROUGH, HANTS

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THE LIMITATIONS OF UPPER-ATMOSPHERE RESEARCH VEHICLES POWERED BY CURRENT BRITISH SOLID-FUEL ROCKETS

by

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MINISTRY OF SUPPLY

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1. Upper Atmosphere
2. Rocket Research

SUMMARY

Two rocket motors were selected as typical of current British boost and sustainer motors respectively, and the minimum amounts of fin structure, etc., needed to convert them into aerodynamically stable vehicles were added. The performance of these single-stage vehicles in vertical climbs from sea level was evaluated by numerical integration. The maximum altitude attained was 120,000 ft, which is not much above the economical limit for balloons. If current rockets are to be of value in upper-atmosphere research, therefore, they must either be used in a two-stage arrangement, or be launched well above sea level, perhaps from a balloon or mountain top. Alternatively, a new solid fuel rocket motor with a long burning time and high length/diameter ratio could be designed specifically for the purpose of high-altitude research - this is probably the best approach.

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LIST OF CONTENTS

		Page
1	Introduction	3
2	Properties of the rocket motors selected	3
3	Stability	4
	3.1 General	4
	3.2 Effect of altering the weight of the nose cone	4
4	Calculation of weight and drag	5
5	Results	5
6	Conclusions	6
References		7
Advance Distribution		7
Detachable Abstract Cards		-

LIST OF TABLES

	Table
Assumed characteristics of rocket motors	I
Weights and performances of vehicles A, B and C	II

LIST OF ILLUSTRATIONS

	Fig.
Sketches of Vehicles A and C	1
Variation of Vehicle Empty Weight and Drag with Nose Weight	2
Variation of the Drag of Vehicles of Fig.1 with Mach Number and Altitude	3
Variation of the Velocity and Altitude of the Vehicles with Time	4
Variation of the Velocity of the Vehicles with Altitude	5
Variation of 'Potential Altitude', $y + \frac{v^2}{2g}$, with time on Actual Trajectories and in Vacuo	6
Acceleration of the Vehicles as a Function of Time	7

1 Introduction

An Anglo-American conference was held at Oxford in August 1953, under the auspices of the Gassiot Committee of the Royal Society, to discuss the use of rockets for upper-atmosphere research. The visiting speakers' accounts of the extensive American work on this subject during the last few years served to emphasize the meagreness of the effort being devoted to it in Britain. The Gassiot Committee therefore wished to know whether any of the rocket motors now in production for G.W. projects would be of value for upper-atmosphere research. Balloons are likely to remain the cheapest method of carrying instruments up to about 100,000 ft altitude, and a rocket vehicle would prove useful if it could cover the altitude range 100,000 to 200,000 ft.

This note gives an indication of the altitudes which might be attained by the simplest type of rocket, a single-stage vehicle with a solid-fuel motor and fixed stabilizing fins, launched at sea level. Typical vehicles are sketched in Fig.1.

2 Properties of the rocket motors selected

Two possible solid-fuel motors are considered here: these are based on the Mayfly boost motor and the sustainer motor for a surface-to-air missile project*, and may be regarded as typical examples of current boost and sustainer motors respectively. The assumed characteristics of the motors are listed in Table I.

TABLE I

Assumed Characteristics of Rocket Motors

		Mayfly type	Sustainer
Thrust (at sea level)	lb	18,000	3,400
Burning time	sec	3	30
Total impulse	lb-sec	54,000	102,000
Propellant specific impulse	sec	210	170
Propellant weight	lb	257	600
Total motor weight	lb	401	850
Propellant/total weight ratio		0.64	0.71
Overall S.I. $= \frac{\text{total impulse}}{\text{total motor weight}}$	sec	135	120
Diameter	inches	10	18
Length (excluding exit nozzle)	inches	112	66

* The final design of this motor is not yet decided, and the assumed performance figures are therefore drastically rounded off.

3 Stability

3.1 General

Since the altitude attained by the vehicle is quite sensitive to changes in empty weight and drag, it is of the utmost importance to ensure that the additional structure needed to transform the basic rocket motor into an aerodynamically stable missile should create as little extra drag and weight as possible. But since cost per flight is the index of merit in an upper-atmosphere research vehicle, the means of stabilization must be cheap and simple. Here the two obvious methods of improving stability were used - weighting the nose and adding fixed fins at the rear. The variation of fin size with nose weight was investigated and the nose weight which appeared to be 'optimum' was chosen.

The fin lift coefficient decreases as Mach number increases, while the body lift coefficient tends to increase slightly; so the critical speed for stability is the maximum speed and the critical moment is just after all-burnt*. If the flight Mach number is increased far enough fin-stabilization becomes impracticable because the fin lift coefficient is so small that adding fins at the rear moves back the centre of gravity more than the centre of pressure (provided the fins are not ridiculously large). This effect is already beginning to assume importance in the vehicles discussed here, which reach Mach numbers of up to 4.5, and it proves advantageous, up to a point, to add ballast in the nose rather than fins at the rear, i.e. to shift forward the C.G. rather than move the c.p. aft.

3.2 Effect of altering the weight of the nose cone

Fig.2 shows how the empty weight and drag of vehicles carrying no payload vary with nose weight. Reducing either drag or empty weight will increase the maximum altitude attainable, and it is to be expected that the weight will have a relatively more powerful effect than the drag. On the basis of this general argument the optimum value of nose weight will be near the value giving minimum empty weight, but rather higher because an increase in the nose weight decreases the fin size and hence the drag. The values chosen for the nose weight, which are marked on Fig.2, were 60 lb for vehicle A (with the boost motor) and 80 lb for vehicle C (with the sustainer motor). Though these vehicles, which are sketched in Fig.1, carry no payload, the additional weight of a payload of 20-50 lb can in vehicle C be compensated by the removal of ballast from the nose, since adequate volume is available; in vehicle A however extra volume would be needed (see section 5).

Although the nose weights were chosen somewhat arbitrarily, an approximate analytical method for determining maximum altitude (based on the computed trajectories) showed that the values chosen were very near the optima.

In making the stability calculations a static margin of 6" was allowed, but since it was of course necessary to guess the maximum speed of the vehicle before the numerical integrations were carried out, the static margins of the vehicles at their actual maximum speeds differ somewhat from 6". The estimated positions of centre of gravity and centre

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* After, not before, because deceleration has a destabilizing effect, for a given stability margin. Jet vanes, which cease to act at all-burnt, can therefore do nothing to alleviate the stability problems. At the highest Mach numbers a diverging tail cone of circular cross-section - a flared skirt - would probably be more efficient than fins in providing stability.

of pressure at maximum speed are indicated in Fig.1. The methods recommended in the G.W. Aero Handbook[1] were used in calculating the lift-curve slopes $\frac{dC_L}{d\alpha}$ for the fins. It was assumed that the body $\frac{dC_L}{d\alpha}$ increased with Mach number up to $M = 3$ as indicated in the Handbook, and remained constant for $M > 3$, in accordance with ref.2. No allowance was made for flexure of the vehicle, i.e. the fin efficiency was taken as 100%.

4 Calculation of drag and weight

The apex angle of the nose cone was taken as 20° and the fins were assumed to be of cropped delta form, with 30° leading-edge sweepback, net aspect ratio 1.5 and thickness/chord ratio 0.03. The drag was calculated by the methods of ref.1, and a 5% addition was made to allow for holes, aerials, etc. The variation of drag with Mach number for the vehicles sketched in Fig.1 is shown in Fig.3.

The weight of fins and attachments was taken as 5 lb/sq ft of net fin plan area. The minimum weight of the nose cone and attachments was taken as 6 lb/sq ft of surface area for the vehicles with boost motors and 3.5 lb/sq ft for the vehicle with the sustainer motor, which encounters much less severe heating.

5 Results

The vehicles A and C sketched in Fig.1 carry no payload. The nose cone of vehicle C, which has a volume of 2.5 cu. ft, should be able to accommodate a payload of up to about 50 lb, and the results for vehicle C therefore apply, as a first approximation, whether or not a payload is carried. Extra volume must be provided however if vehicle A is to carry a 50 lb payload, and separate calculations have therefore been made for such a vehicle, which is labelled B.

The performances of vehicles A, B and C in vertical climbs have been calculated by numerical integration of the equation of motion. Table II gives weight breakdowns for the three vehicles, together with their maximum altitudes and velocities.

TABLE II

Weights and Performance of Vehicles A, B and C

Vehicle:		A	B	C
Motor (see Table I)		Mayfly type	Mayfly type	Sustainer
Payload	lb	0	50	80
Nose weight (excluding payload)	lb	60	39*	
Weight of fins	lb	32	40	70
Weight of motor case	lb	144	144	250
Empty weight of vehicle	lb	236	273	400
Propellant weight	lb	257	257	600
Initial weight of vehicle	lb	493	530	1000
Length		152"	186"	137"
Diameter		10"	10"	18"
Maximum velocity (at all-burnt)	ft/sec	4530	4070	2610
Altitude at all-burnt	ft	6100	5600	36,800
Maximum altitude	ft	119,400	94,000	99,500

*The nose section of vehicle B consists of a nose cone plus a cylindrical section nearly 3 ft long. The volume allowance for the 50 lb payload was 2 cu. ft.

The velocities, altitudes and accelerations of the three vehicles on vertical-climb trajectories are shown in Figs.4-7. Fig.4 gives the variation of velocity v and altitude y with time, and these results are replotted in Fig.5 to show directly how velocity varies with altitude. The 'potential altitude' $y + \frac{v^2}{2g}$, i.e. the altitude the vehicle would reach if drag ceased at time t, is plotted against t in Fig.6, and compared with its value in vacuo, i.e. if there were no drag from $t = 0$ onwards. Fig.6 shows that the altitudes actually attained by the vehicles are less than one third of the altitudes they would reach in vacuo. Large increases in altitude would therefore be obtained if the drag were drastically reduced, e.g. by launching at high altitude. Fig.7 shows the longitudinal accelerations of the vehicles as functions of time.

It will be seen from Figs.4-7 that vehicles A and B reach a much greater speed than vehicle C, but at such low altitudes that the large drag quickly reduces it. The velocity-time variation of vehicle C is much more favourable and it is somewhat disappointing to find that its performance is inferior. The reason is that its small length/diameter ratio increases the body drag and, indirectly via the stability, the fin drag. Vehicle C would have an all-burnt velocity of 5020 ft/sec in gravity-free airless space; the loss in velocity due to gravity is 970 ft/sec, and the loss due to drag is 1450 ft/sec. Thus if the drag were halved the all-burnt velocity might be increased by about 25% and the potential altitude at all-burnt by about 50%. The loss in potential altitude after all-burnt would also be smaller and the maximum altitude attained might be approximately doubled. (It is not however a general rule that halving the drag doubles the altitude: this could never occur if the altitude originally attained were more than half the potential altitude in vacuo.).

It is apparent therefore that a sustainer rocket motor designed specifically for the upper-atmosphere research role could propel vehicles to altitudes much greater than 100,000 ft, even if its specific impulse and charge/weight ratio were no better than those of current motors. A more detailed investigation would be necessary before attempting to specify the desirable characteristics of such a motor. From the somewhat inadequate evidence in this note it would seem likely that a burning time of 15-20 sec and a length/diameter ratio of about 10 might be called for, and this might involve the use of a modified cigarette-burning charge.

6 Conclusions

A single-stage vehicle powered by an existing boost or sustainer motor, launched at sea level and having conventional forms of aerodynamic stabilization, is not likely to attain altitudes very much in excess of 100,000 ft when carrying a payload of 20-50 lb. Such a vehicle if it were to be of value would therefore have to be launched from a high mountain or a balloon; alternatively, of course, a two-stage configuration could be used. These possible improvements would however increase the cost and complication.

The present rocket motors, because they were designed for very different purposes, are somewhat inefficient for upper-atmosphere research; but a new solid-fuel rocket capable of powering a useful ground-launched vehicle could probably be designed if required.

REFERENCES

No.	Title, etc.
1	Handbook of Supersonic Aerodynamic Data Applicable to Guided Weapon Design. R.A.E. Guided Weapons Dept., GW/Handbook/1.
2	Long-Range Surface-to-Surface Rocket Vehicles. Preliminary Investigations and Results: Aerodynamics. Project Rand, Report RA 15065 (March 1948).

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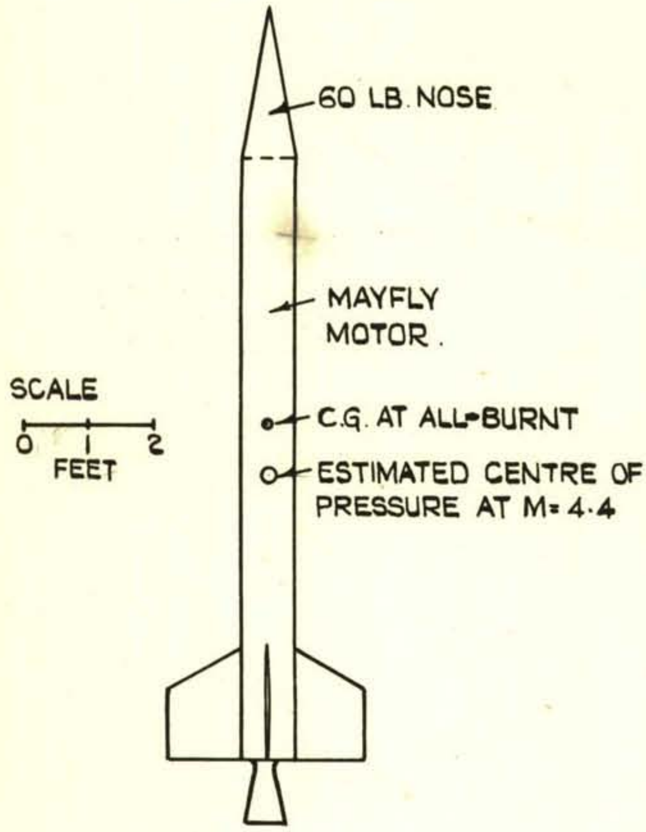
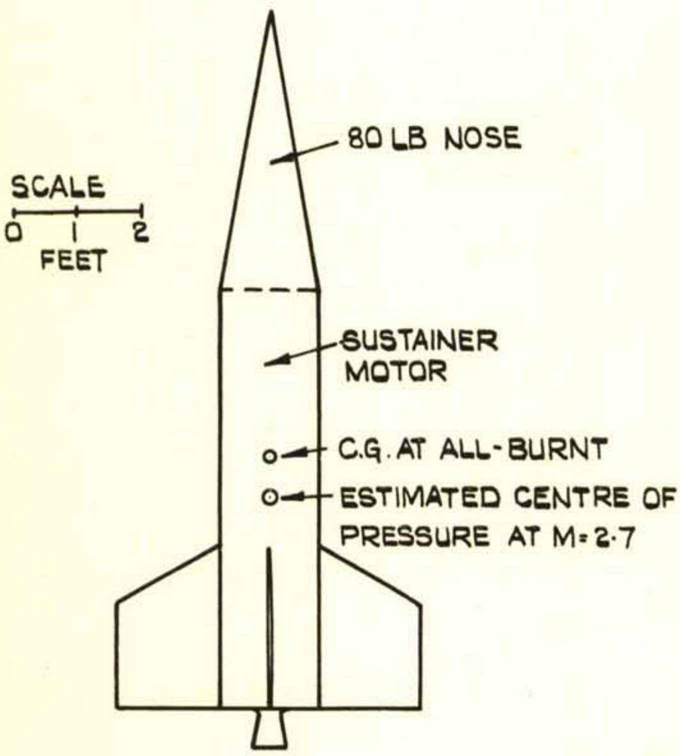


WEIGHTS	LB
NOSE CONE	60
FINS, ETC.	32
MOTOR CASE	144
PROPELLANT	257
ALL-UP WEIGHT	493

DIMENSIONS, ETC.	
LENGTH	152"
BODY DIAMETER	10"
FIN SPAN	37"
NET PLAN AREA OF ONE PAIR OF FINS	3·2 SQ.FT
MAX. VELOCITY	4530 FT/SEC
MAX. ALTITUDE	119,400 FT

(a) VEHICLE 'A', WITH MAYFLY MOTOR & ZERO PAYLOAD.



WEIGHTS	LB
NOSE CONE.	80
FINS, ETC.	70
MOTOR CASE	250
PROPELLANT.	600
ALL-UP. WEIGHT	1,000

DIMENSIONS, ETC.	
LENGTH	137"
BODY DIAMETER	18"
FIN SPAN	58"
NET PLAN AREA OF ONE PAIR OF FINS	6·9 SQ.FT.
MAX. VELOCITY	2610 FT/SEC.
MAX. ALTITUDE	99,500 FT

(b) VEHICLE 'C', WITH SUSTAINER MOTOR & ZERO PAYLOAD.

FIG 1 (a & b) SKETCHES OF VEHICLES A AND C.

FIG. 2. (a & b)

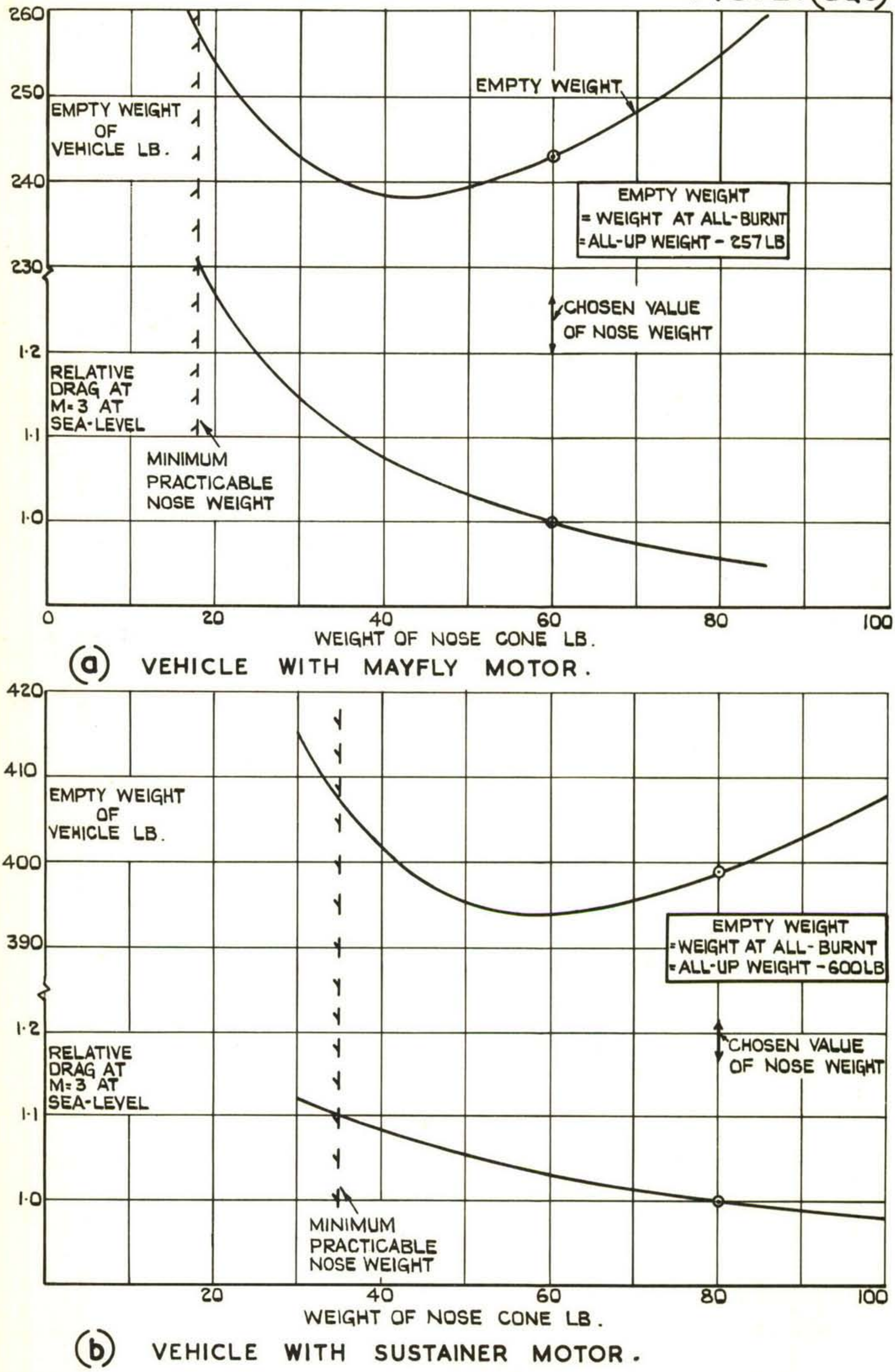


FIG. 2 (a & b) VARIATION OF VEHICLE EMPTY WEIGHT AND DRAG WITH NOSE WEIGHT.

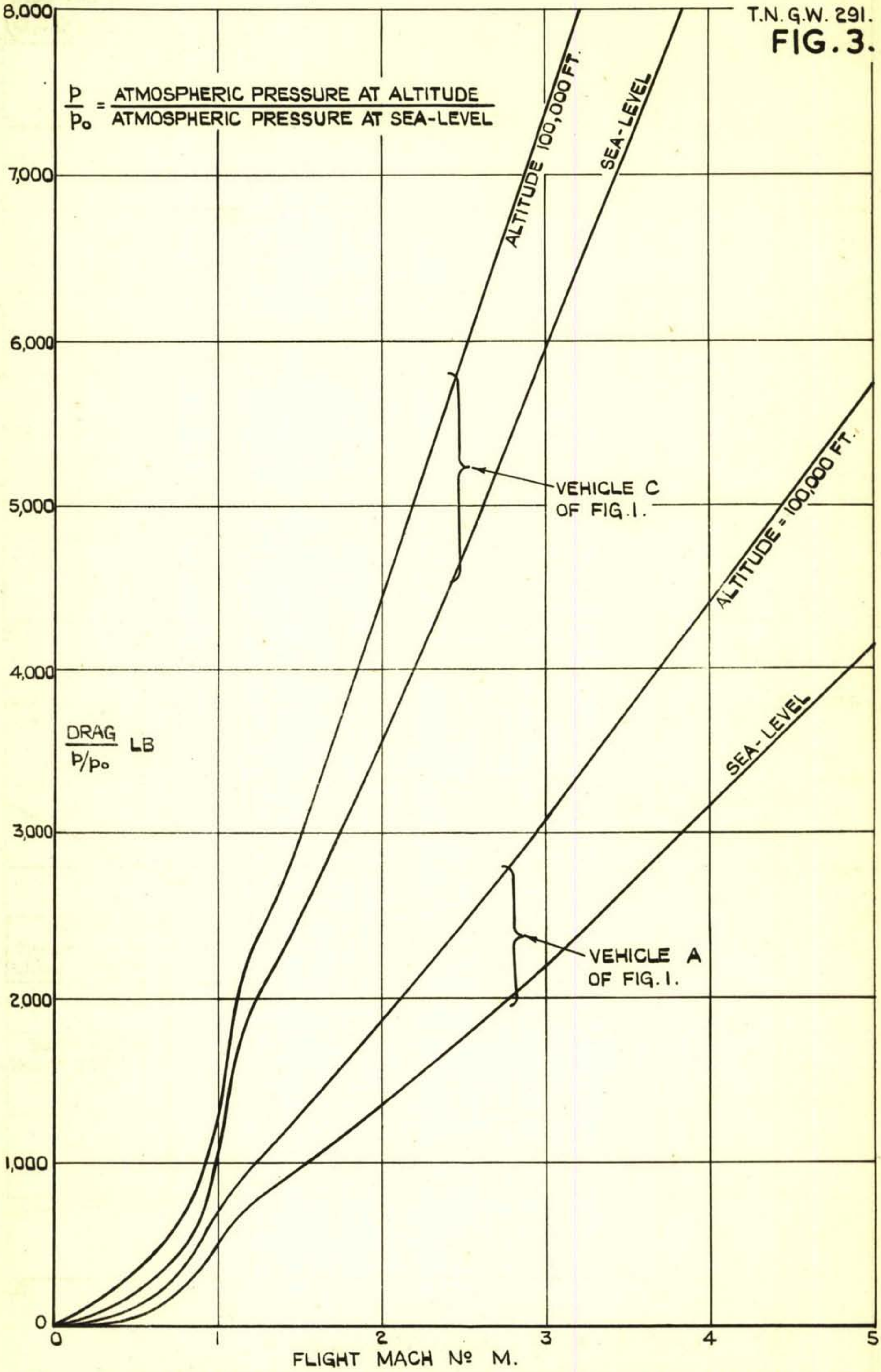


FIG. 3. VARIATION OF THE DRAG OF VEHICLES OF FIG. 1. WITH MACH NUMBER & ALTITUDE.

FIG. 4.

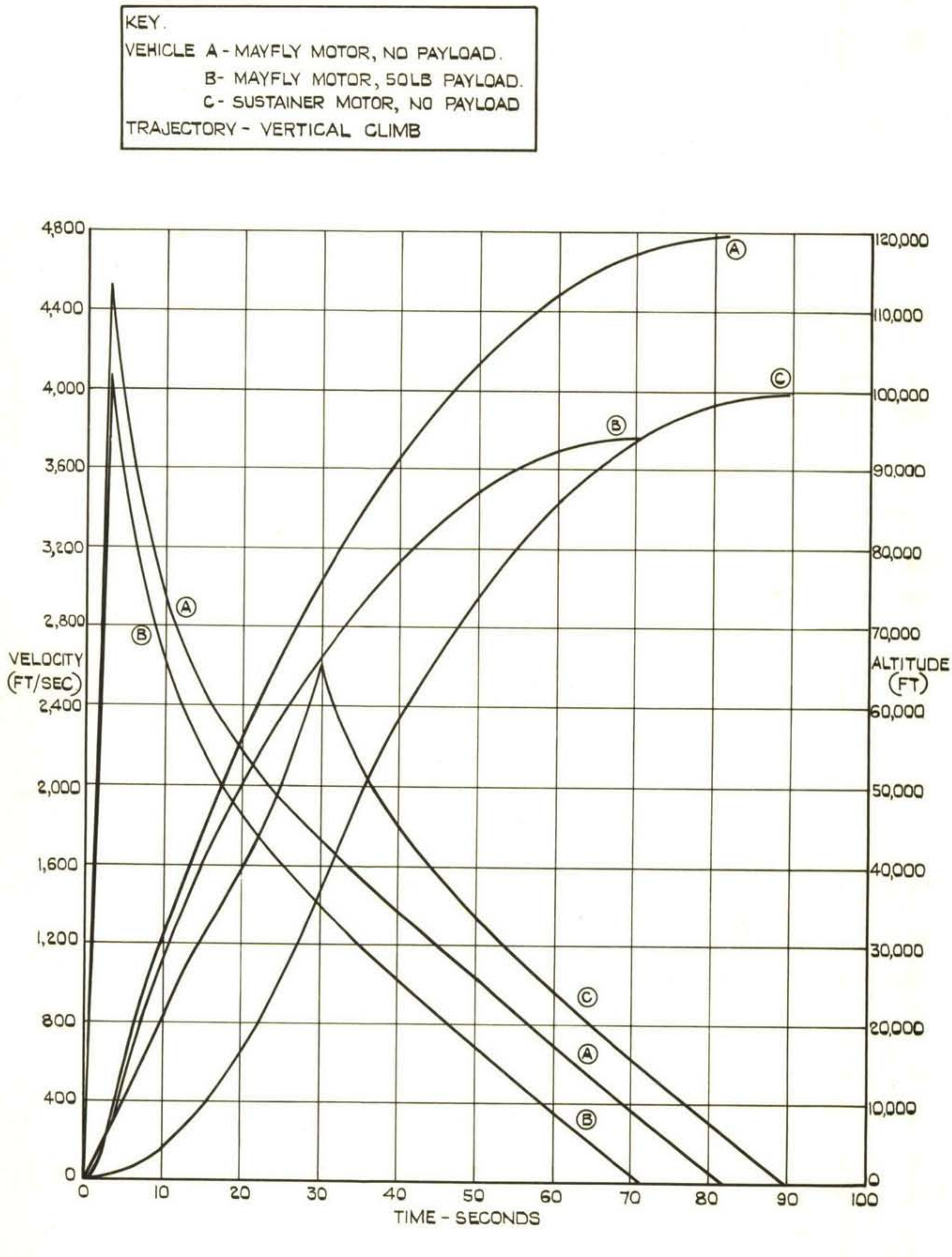


FIG. 4. VARIATION OF THE VELOCITY & ALTITUDE OF THE VEHICLES WITH TIME.

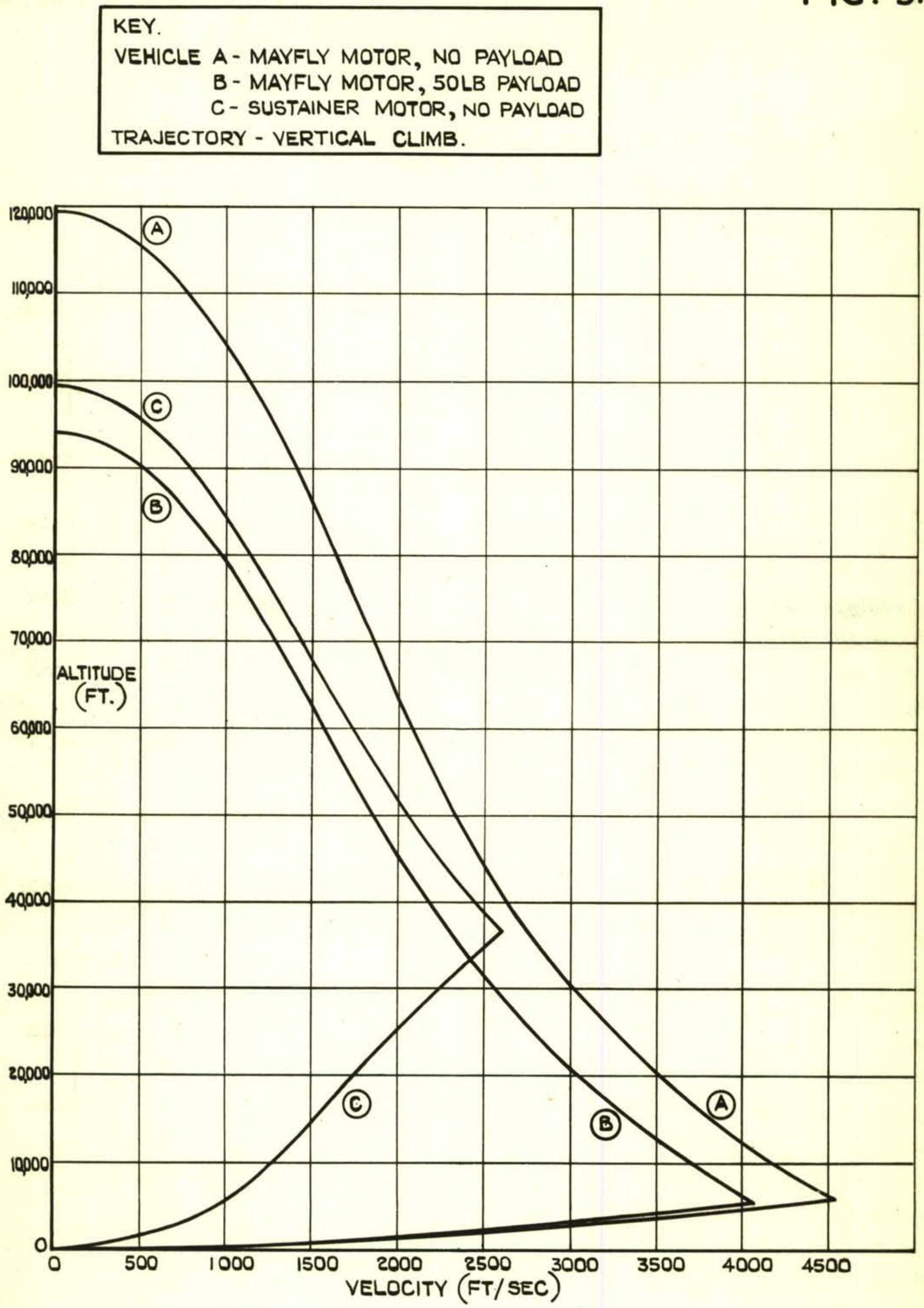


FIG. 5. VARIATION OF THE VELOCITY OF THE VEHICLES WITH ALTITUDE.

FIG. 6.

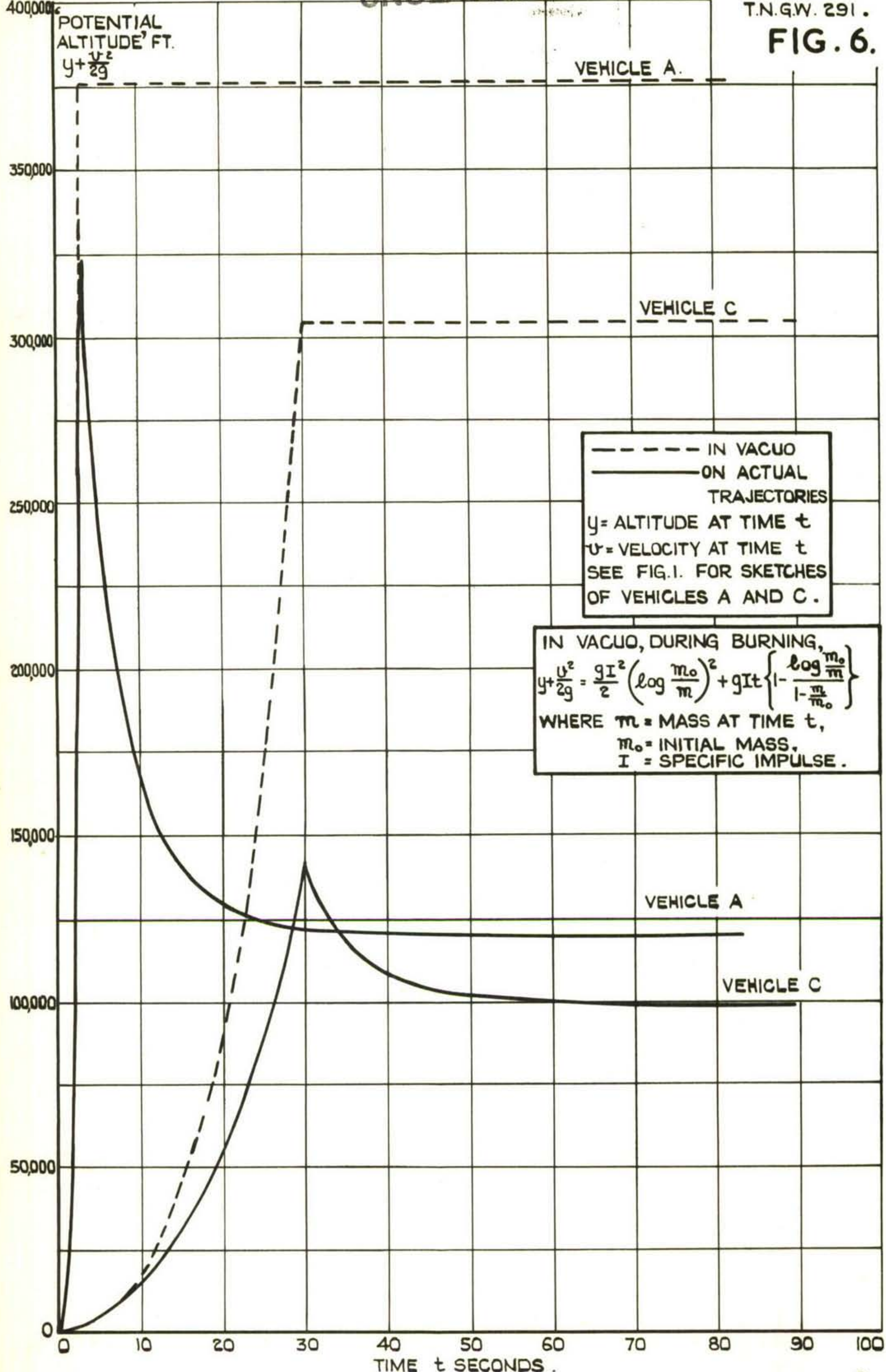


FIG. 6. VARIATION OF 'POTENTIAL ALTITUDE', $y+\frac{v^2}{2g}$, WITH TIME ON ACTUAL TRAJECTORIES AND IN VACUO.

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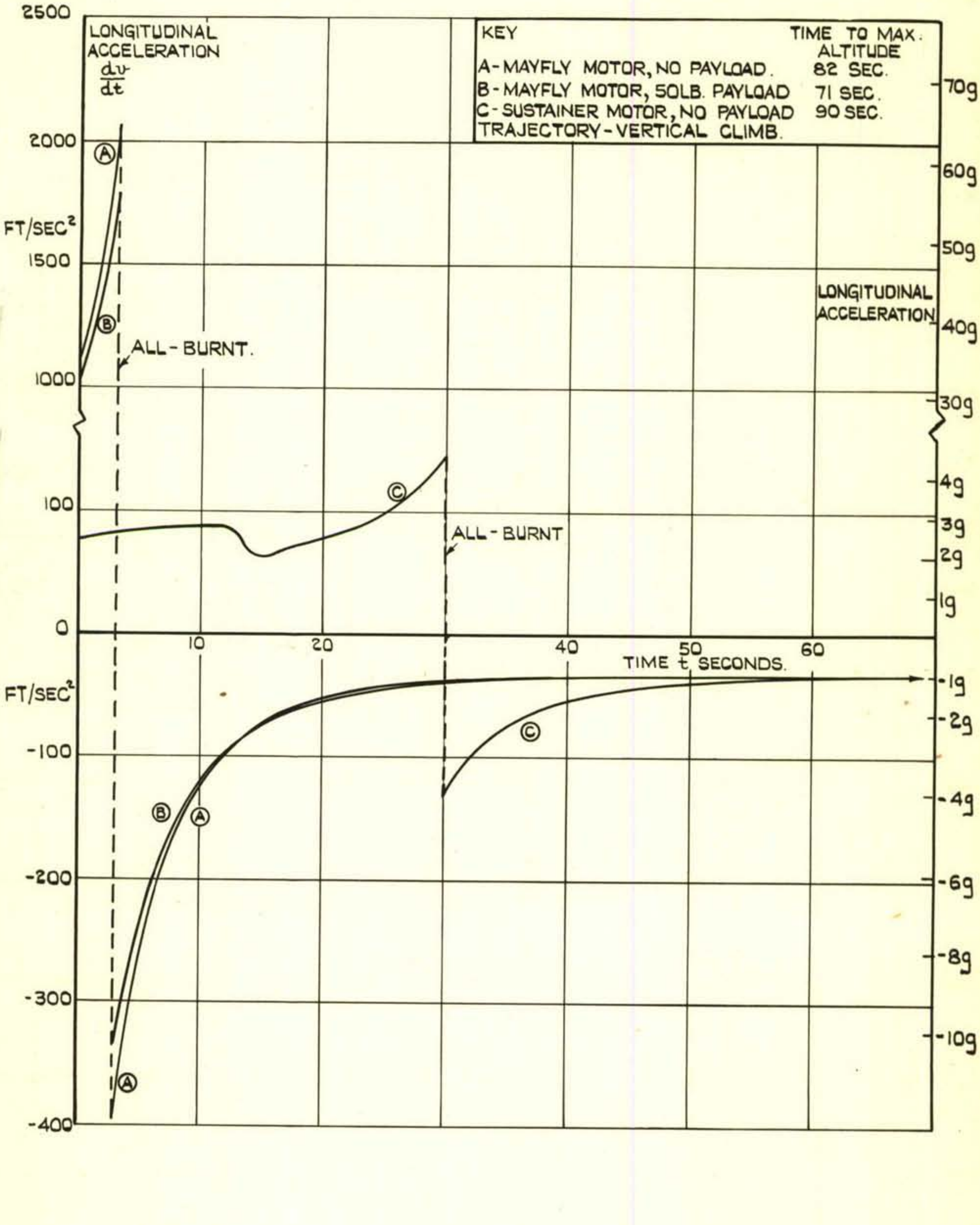

FIG. 7. ACCELERATION OF THE VEHICLES AS A FUNCTION OF TIME.

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